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Electrostatic Discharge (ESD) Protection for a Laser Diode Ignited Actuator

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Electrostatic Discharge (ESD) Protection for a Laser Diode Ignited Actuator

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Abstract

The use of laser diodes in devices to ignite pyrotechnics provides unique new capabilities including the elimination of electrostatic discharge (ESD) pulses entering the device. The Faraday cage formed by the construction of these devices removes the concern of inadvertent ignition of the energetic material. However, the laser diode itself can be damaged by ESD pulses, therefore, to enhance reliability, some protection of the laser diode is necessary. The development of the MC4612 Optical Actuator has included a circuit to protect the laser diode from ESD pulses including the "Fisher" severe human body ESD model. The MC4612 uses a laser diode and is designed to replace existing hot-wire actuators. Optical energy from a laser diode, instead of electrical energy, is used to ignite the pyrotechnic. The protection circuit is described along with a discussion of how the circuit design addresses and circumvents the historic 1Amp/1Watt requirement that has been applicable to hot-wire devices.

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Basic Requirements for Protection Circuit

The protection circuit must eliminate laser diode failures due to electrostatic discharge (ESD) and the laser diode must function normally with the protection circuit in place. It is anticipated that the MC4612 will be used in different systems having different firing circuits that originally fired hot-wire actuators. To eliminate the redesign of these firing systems, the protection circuit and laser diode should be compatible with different firing systems and function reliably with all of them.

The design goal is to configure the laser diode and protection circuit in a space similar to that of hot-wire devices, including the connector and connector boot. In the present design, the connector boot will house the protection circuit, and the laser diode will be placed in the connector. Miniaturization techniques were applied to the design to meet this space constraint.

Tester and Testing Procedure

A PT3689 "Fisher" Electrostatic Discharge Tester was used for ESD testing[1]. This tester was designed to provide a 25kV, 120A peak ESD pulse that is considered to be equivalent to a severe human body generated ESD pulse. Each ESD pulse was observed with a current viewing transformer internal to the ESD tester. This was done to ensure that an ESD pulse was applied to a unit under test and that the ESD tester was functioning properly.

Testing consisted of applying ESD pulses to the laser diode in both the forward and reverse biased directions. First, a single ESD pulse was applied to a unit under test in the forward direction (ESD applied to laser diode anode), and the optical energy output was measured and compared with pre-test data. If the unit post-test output did not change, it was subjected to twenty ESD pulses. Twenty pulses were applied to verify that the protection circuit and the laser diode would withstand multiple pulses during their life cycle and ensure that incremental damage does not occur. Reverse testing (ESD applied to laser diode cathode) was done in the same manner.

Modeling

The ESD pulse generating circuit was modeled using PSpice software. Figure 1 is the circuit used in the simulator. The pulse generating circuit in Figure 1 is shown connected to a "short". Figure 2 shows the ESD current pulse waveform produced by the model. This simulated pulse is very close to the actual ESD current pulse observed on an oscilloscope. A protection circuit design can be simulated in the model by connecting it at the output terminals in place of a short (Figure 1).

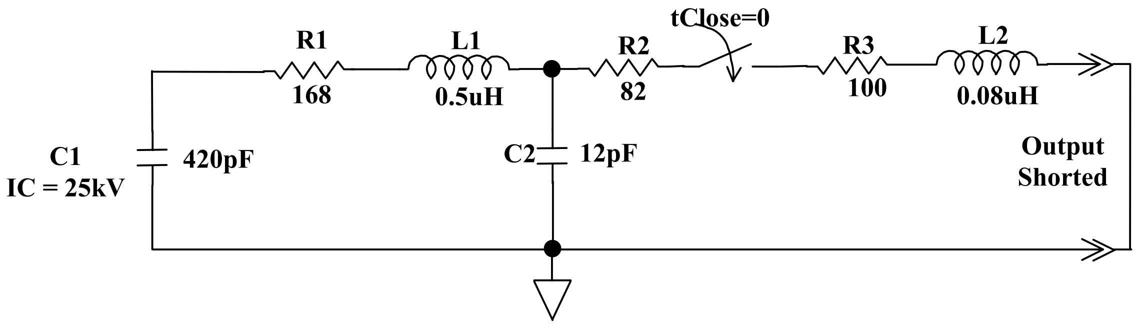

Figure 1. Circuit Used to Model ESD Tester

Protection Circuit Design

To protect a laser diode from the ESD pulse shown in Figure 2, the voltage produced by the ESD pulse must be "clamped" or reduced to a safe level. A transient voltage suppressor (TVS) was chosen to perform this function. This device effectively clamps the ESD voltage, shorting most of the current to circuit ground thus reducing current flow through the laser diode to a safe level. Figure 3 is a schematic of a firing circuit connected to a laser diode and the protection circuit.

In the event of an accident or abnormal situation, a fail-safe condition will exist in the protection circuit. A TVS will fail if subjected to transient pulses that exceed its design limits. If the energy and duration of a transient pulse does exceed the TVS limits, the TVS will fail shorted. This is a fail-safe mode since the pulse that caused the failure and all additional inputs will be shorted to circuit ground. A very large transient pulse of short duration can cause the TVS silicon chip to explode resulting in an open. With weapon system protection devices installed, the existence of a transient pulse of this nature at the protection circuit input is not viable and the fail-safe condition will prevail.

The protection circuit is always attached to the laser diode, and the information needed to design an ESD protection circuit when considering a specific firing system includes:

1. The firing circuit specification of minimum and maximum output voltage
2. The total series resistance from firing circuit source to the protection circuit
3. TVS maximum and minimum breakdown voltages
4. Laser diode maximum pulsed current capability
5. Laser diode power rating
6. Laser diode minimum current needed to cause the desired device activation and performance (all-fire current)

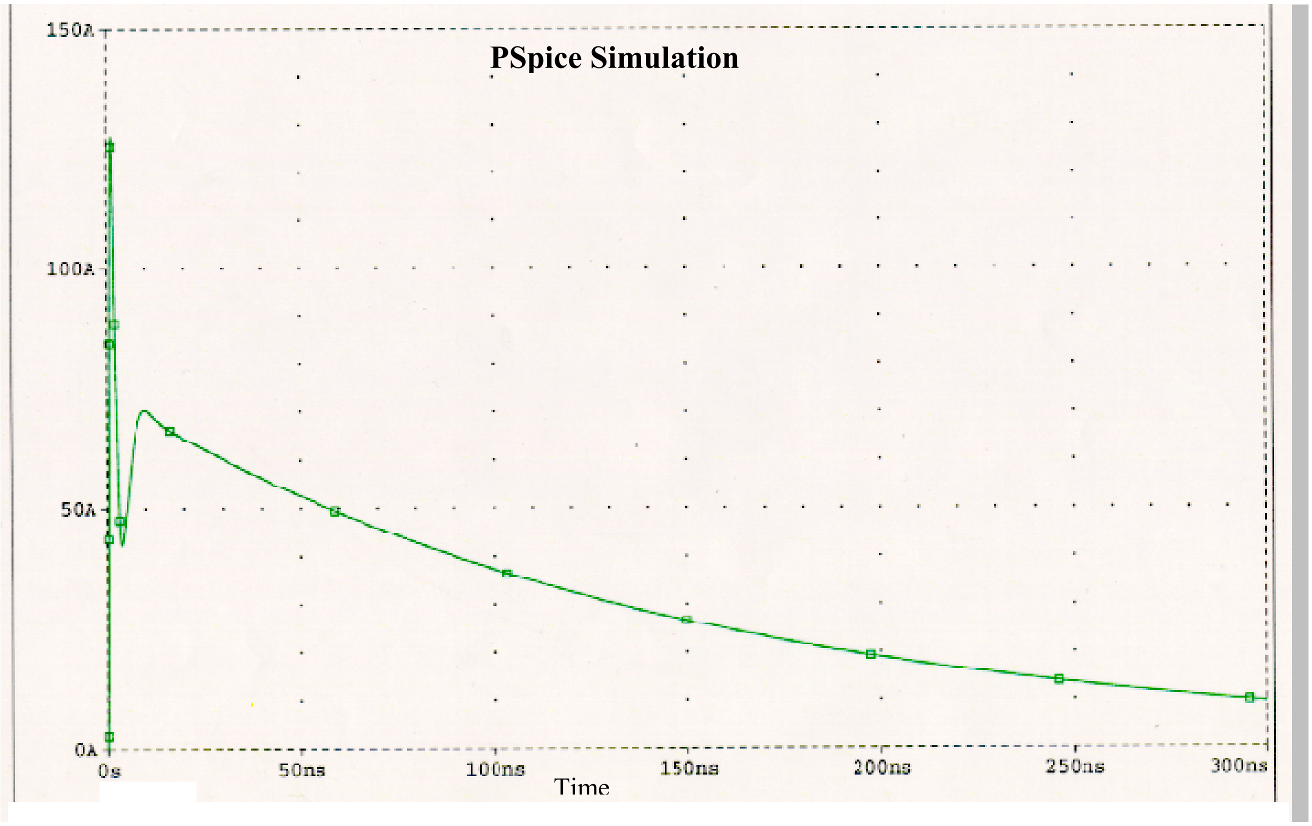

Figure 2. Simulated Waveform of Fisher Model ESD Pulse

The firing circuit maximum output voltage will determine the minimum TVS clamping voltage when the pulse from the firing circuit is applied to the protection circuit / laser diode. The specific firing circuit considered in this design has a minimum voltage (V_{MIN}) and a maximum voltage (V_{MAX}) of 23.5 and 32 Volts, respectively. The minimum TVS breakdown voltage must be greater than the maximum firing circuit output voltage or else the firing circuit will be clamped to this TVS minimum value, causing the firing circuit to be partially shorted to ground through the TVS.

The firing circuit maximum output voltage and the series resistance (R_S) from the firing circuit source to the protection circuit will also dictate the maximum amount of pulsed current that can be applied to the laser diode. As stated above, the MC4612 will be used in different firing systems. The value of R_S varies in the firing circuits from one system to another. The laser diode protection circuit design needs to function with all firing circuits, making it necessary to determine maximum and minimum values of R_S.

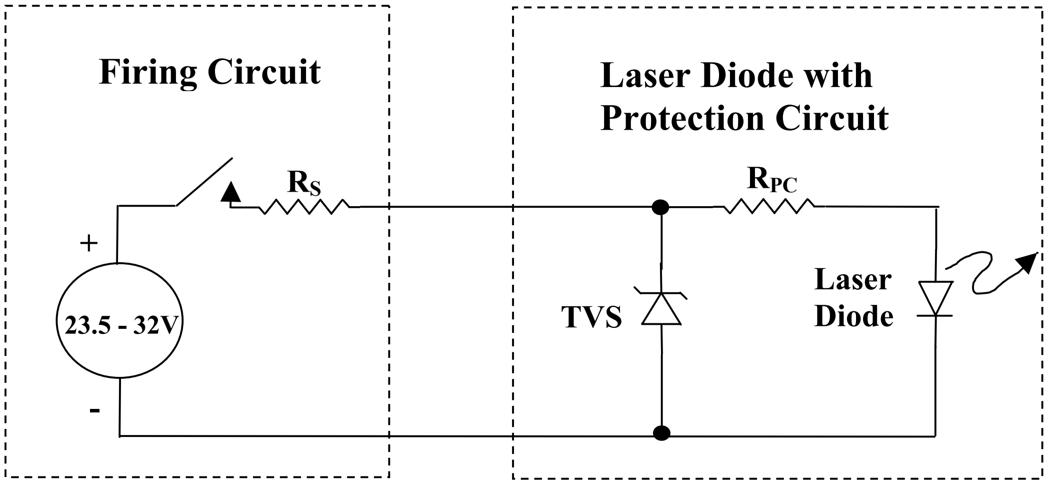

Figure 3. TVS ESD Protection Circuit

The function of the resistor in the laser diode protection circuit is to limit current through the laser diode when a pulse is applied from a firing circuit or from inadvertent pulses such as ESD. This protection circuit resistance (R_{PC}) adds to the normally low R_S, and is needed to limit current when a firing pulse is applied. For example, the laser diode resistance R_{LD} is nominally 1Ω. If the firing circuit voltage is at maximum (32Volts), and R_S equals 3Ω, a current of 8A will flow through the laser diode. This magnitude of current exceeds the laser diode capability and it will be destroyed. R_{PC} then has to be selected such that the current through the laser diode is limited to a safe level.

The laser diode needs a finite amount of current for a finite period of time to generate the required optical energy to reliably ignite the pyrotechnic. This minimum all-fire current ($I_{LD\ MIN}$), and the firing circuit V_{MIN} also are considered when selecting the value of R_{PC}. The value of R_{PC} must be low enough to allow $I_{LD\ MIN}$ to flow through the laser diode when the firing circuit voltage is at V_{MIN}. Equation 1 is used to determine the value of R_{PC}.

1) $$R_{PC} = (V_{MIN} / I_{LD\ MIN}) - (R_{S\ MAX} + R_{LD})$$

For this application, V_{MIN} = 23.5V, $I_{LD\ MIN}$ = 1.3A, $R_{S\ MAX}$ = 5Ω, and R_{LD} = 1Ω. Thus, R_{PC} is calculated to be 12Ω.

With the value of R_{PC} determined, the maximum current through the laser diode ($I_{LD\ MAX}$) can be found from Equation 2.

2) $$I_{LD\ MAX} = V_{MAX} / (R_{S\ MIN} + R_{LD} + R_{PC})$$

The typical firing circuit pulse time duration is 10 milliseconds. The actual time to ignition in the MC4612 is considerably less than 10 milliseconds even at the minimum firing voltage. However, in a robust circuit design, both R_{PC} and the laser diode must be capable of withstanding the power generated by this pulse. The current $I_{LD\ MAX}$ flowing for 10 milliseconds must not cause the power rating of either R_{PC} or the laser diode to be exceeded. For this application, V_{MAX} = 32V, and R_{SMIN} = 3Ω. This yields $I_{LD\ MAX}$ = 2A. Since the power applied to R_{PC} is pulsed, the pulse handling capabilities of this resistor need to be addressed. The maximum pulsed energy rating for R_{PC}, a Vishay WSN2515, is given in terms of energy/Ohm, and is $1.27E^{-2}$ J/Ω. The equation used is energy/Ohm = $I^2Rt/4R$. I = $I_{LD\ MAX}$ = 2A, R = R_{PC} = 12Ω, and t = 10ms. This yields energy/Ohm = $1.0E^{-2}$ J/Ω, and is less than the rating of $1.27E^{-2}$ J/Ω for R_{PC}.

The laser diode used is rated at 2W continuous wave. A typical 2A, 10ms fire pulse will generate 2W ($I_{LD\ MAX}$ = 2A, R_{LD} = 1Ω) for 10ms. Numerous laser diodes were tested at input levels up to 2.5W (10ms) and no damage was observed. Details of this testing will be discussed later.

Testing With Protection Circuit

To test the effectiveness of the protection circuit shown in Figure 3, a 12Ω resistor was used as R_{PC}. Laser diodes manufactured by Semiconductor Laser International (SLI) were tested to ESD exposure by the testing procedure described above. Sixty laser diodes with the protection circuit in place were tested, and all survived the ESD pulse. Two laser diodes were tested without the protection circuit and both of these devices were damaged.

Circuit Simulation

The circuit that was modeled using a PSpice computer simulation is shown in Figure 4 and depicts the protection circuit coupled to the ESD generator. The simulated current and voltage waveforms seen in Figure 5 indicate that current through the laser diode due to an ESD pulse lasts for approximately 600ns and the TVS clamping voltage varies as the ESD pulse decays. For the TVS used in the model, 43V is the maximum clamping voltage, and this value is observed at the peak ESD current pulse of 120A. This results in a peak current of 3.5A flowing through the laser diode in the forward direction for a few nanoseconds then a slight decrease in this value as the ESD current decreases, and the resultant TVS clamping reaches 33V. The energy content of the ESD pulse reaching the laser diode after passing through the protection circuit is reduced to near zero. Without the protection circuit, the ESD pulse delivers a peak current of 120A and the current then decreases from 60A to 10A at 300ns and the current at 600ns is zero. This pulse, of course, damages the laser diode.

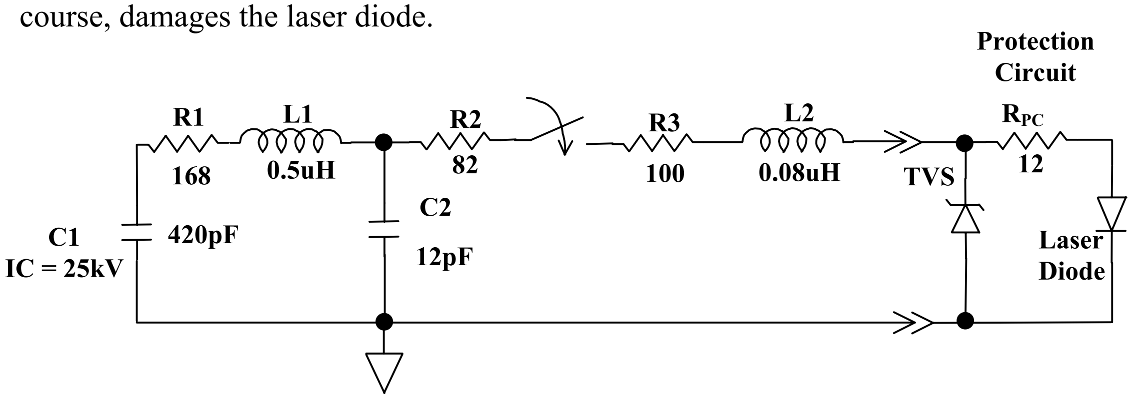

Figure 4. Circuit of ESD Tester Connected to Protection Circuit

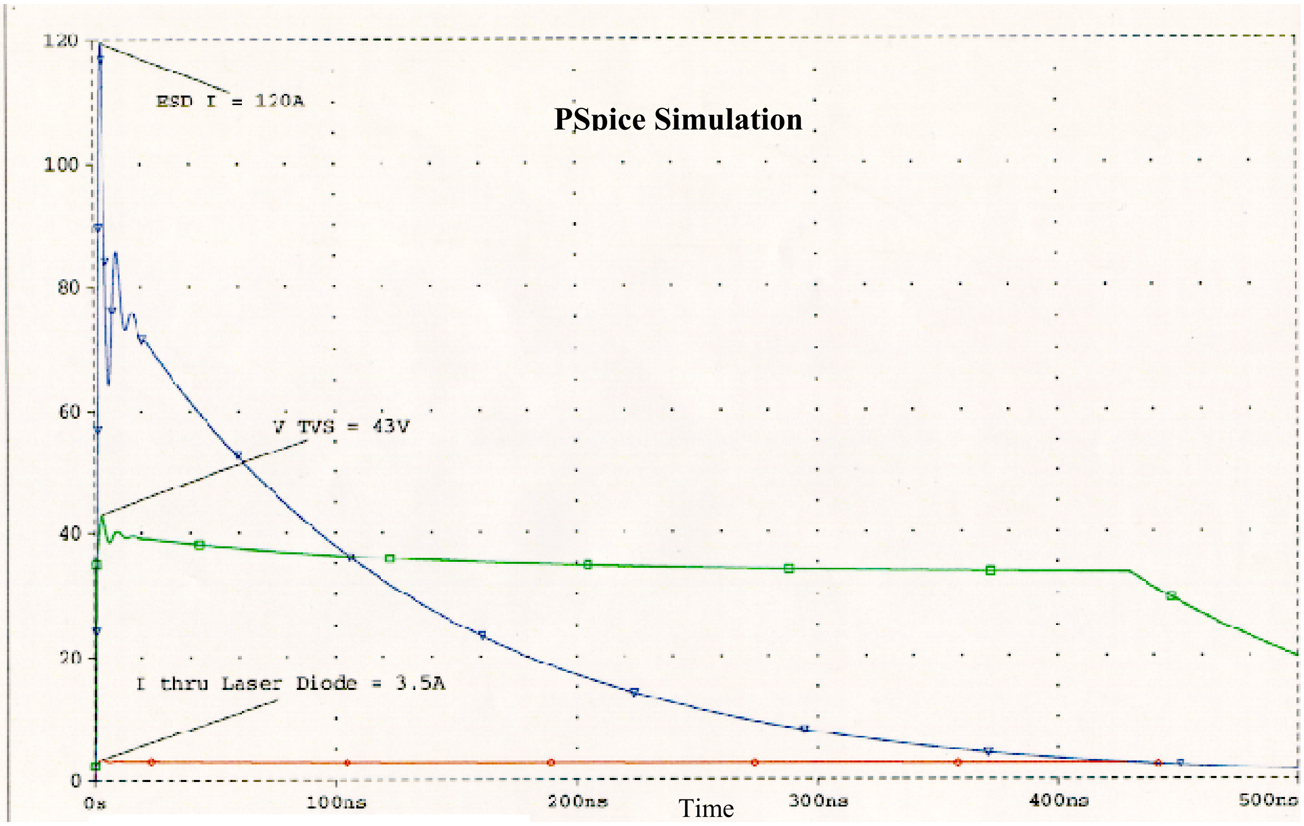

Figure 5. Simulation Results of Protection Circuit Effectiveness

1A/1W Requirement and Improved ESD Protection

As stated above, the MC4612 is replacing a hot-wire actuator which has a requirement that it will not fire if it is powered from an induced current of 1A generating 1W for 5 minutes. This test is considered to be destructive, and tests the ability of the explosive actuator to dissipate 1W of power. The test is accomplished by putting a 1A constant current source through the bridgewire of the actuator. The actuator bridgewire resistance is nominally 1Ω, and thus the 1W power level is met and is dissipated by the actuator. It can be assumed that the applied voltage is low, e.g., 1V, (1Vx1A=1W), and the test simulates a scenario where low voltage is applied to the actuator due to a tester malfunction or electromagnetic radiation.

A current of 1A through the laser diode in the MC4612 is sufficient to generate enough optical power to cause pyrotechnic ignition, therefore, inadvertent current pulses must be prevented. To prevent low voltage level sources from appearing at the laser diode, the protection circuit shown in Figure 6 was designed. This design rejects DC voltage levels up to 12V, ESD pulses, and other transient pulses up to 7.5µs in duration.

The circuit shown provides a voltage level turn-on threshold and improved protection for the laser diode. The field effect transistor (M1) in Figure 6 has an inherent gate threshold voltage at which it will turn on. At this gate threshold voltage, M1 is turned on and current can flow through the laser diode. In the circuit shown, an input voltage of 12V is necessary to cause a voltage drop large enough from the gate-to-source (voltage drop across R1) to start current flow through M1. Changing the values of R1and R2 will change this 12V turn-on level. M1 isolates the laser diode from long period low-level voltage inputs of 12V or less. Each production circuit will be tested to verify this capability and the traditional 1A/1W test will be removed from the test schedule for the MC4612 Actuator.

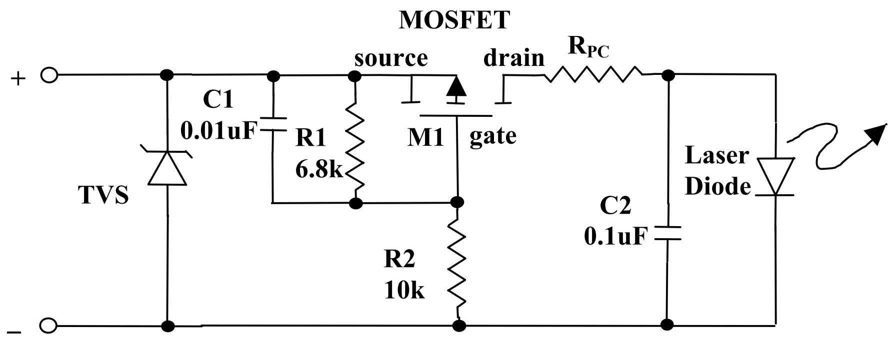

Figure 6. Improved ESD Protection Circuit

With the addition of capacitors C1 and C2, short pulses less than 10μs are prevented from appearing at the laser diode. The time constant due to R1 and C1 causes a delay in time before the gate-to-source voltage of M1 reaches turn-on level. This delay isolates the laser diode from ESD or other fast transient pulses up to approximately 7.5μs duration. The width of an ESD pulse is less than 1μs. This delay length can be tailored to fit specific needs. Fast pulses can be coupled through to the laser diode by circuit stray capacitance. These pulses are filtered out by capacitor C2. This circuit provides improved ESD protection compared to the circuit shown in Figure 3. The circuit shown in Figure 6 allows no current to flow through the laser diode due to ESD or other transient pulses less than 7.5μs in duration. The first design (Figure 3) that does not include the transistor M1 with associated circuitry allowed a peak current of 3.5A to flow through the laser diode.

Figure 7 is a PSpice simulation of this improved circuit connected to an ESD generator. No current is observed flowing through the laser diode. To validate that no current flows through the laser diode when an ESD pulse is applied, numerous active tests were performed. A current viewing transformer (CVT) was attached to the ground lead of the ESD protection circuit with a laser diode in place. An ESD pulse was then applied from the ESD tester and the CVT output recorded. Figure 8 shows the ESD generated current and the resultant current through the laser diode. No current flow is observed during the ESD pulse.

With the addition of M1, equations 1 and 2 become equations 3 and 4 respectively. R_{FET} is the resistance of M1 when it is in the "on" condition.

3) $R_{PC} = (V_{MIN} / I_{LD\,MIN}) - (R_{S\,MAX} + R_{LD} + R_{FET}) \qquad R_S << R1+R2$

4) $I_{LD\,MAX} = V_{MAX} / (R_{S\,MIN} + R_{LD} + R_{PC} + R_{FET}) \qquad R_S << R1+R2$

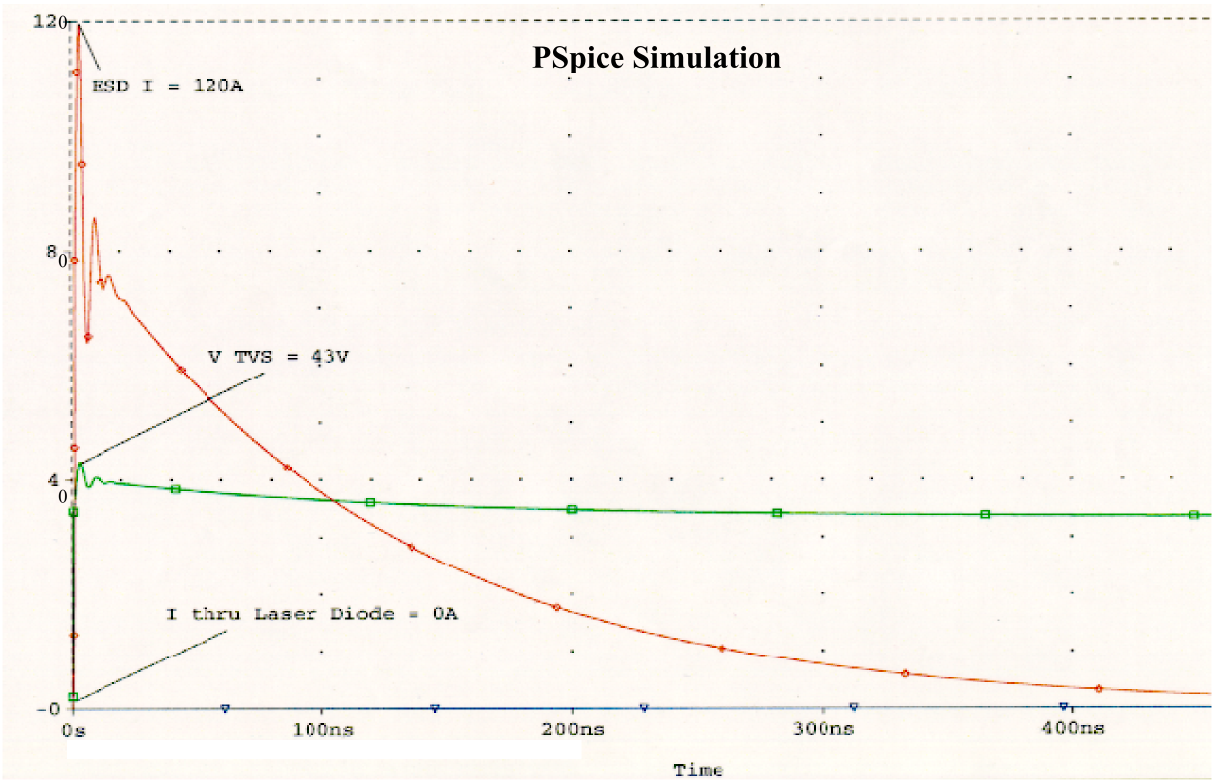

Figure 7. Simulation of Improved ESD Protection Circuit

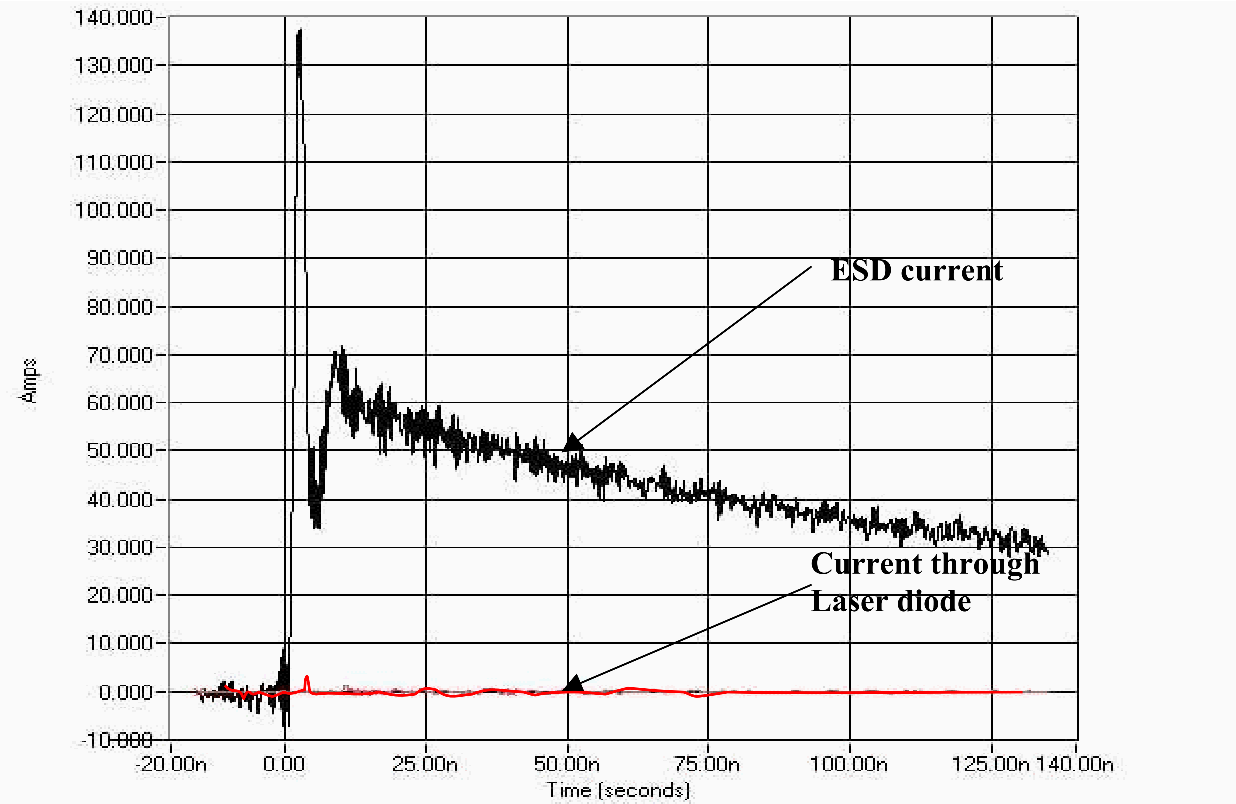

Figure 8. Current Through Laser Diode With Improved ESD Protection Circuit

Reliability Testing

One hundred laser diodes coupled to the protection circuit were subjected to ESD testing. No laser diode failures due to ESD were observed. To verify reliability in actual use, the protection circuit and laser diode were tested with a tester setup that simulates a firing circuit. The laser diode and the protection circuit were pulsed one million times. A 2.5A/10ms pulse was applied every 10sec. This pulse represents the highest current and the longest duration pulse allowed for the laser diode. Laser diode energy was monitored and recorded for every shot and the laser diode header temperature was continuously monitored throughout the testing period. During the test, the laser diode optical energy varied +/- 0.1mJ shot to shot and the header temperature did not rise due to power dissipation in the header. The laser diode as well as the protection circuit survived these tests with no degradation. In addition, testing was performed on the diodes at +165^{o}F and –65^{o}F. These diodes were pulsed one hundred thousand times using the same current and time duration as described above. Once again, these diodes and protection circuit survived with no noticeable degradation.

Figure 9 is a sketch of the MC4612. The protection circuit is integrated into the connector boot and the laser diode is inserted in the connecter.

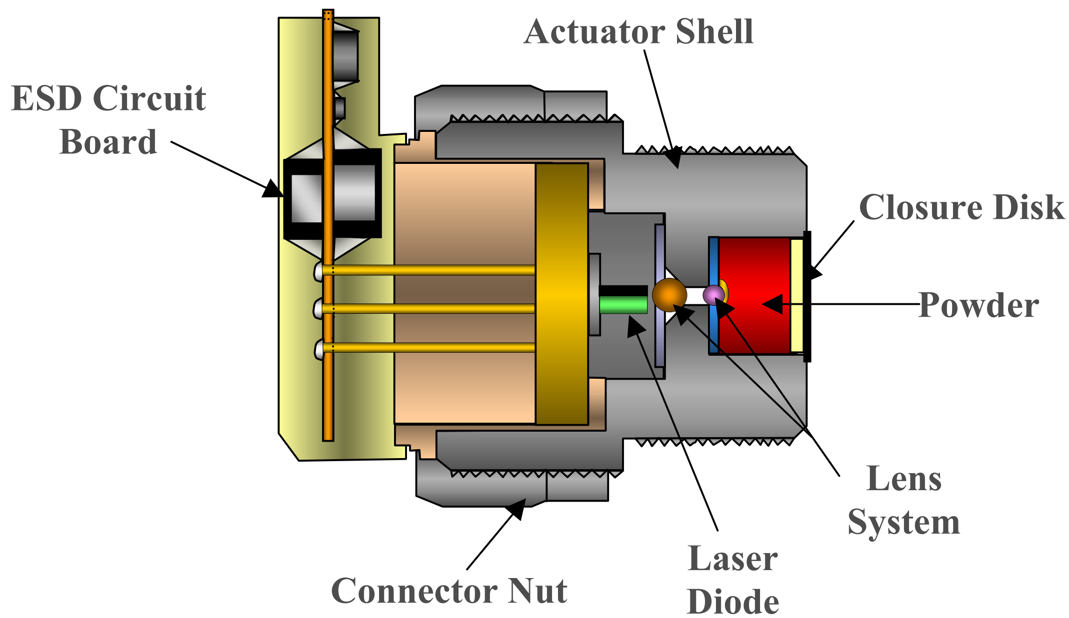

Figure 9. MC4612 Optical Actuator

Conclusion

A protection circuit that eliminates failure of laser diodes caused by ESD pulses has been designed and validated. The 1A/1W test does not apply to a laser diode actuator due to the fact that the design rejects low voltage sources that can generate power in the laser diode. Intended firing voltages will result in nominal performance. The circuit is miniaturized and fits in the MC4612 connector boot. The combination of protection circuit and laser diode is compatible with the firing systems of interest, eliminating firing circuit redesign. The use of a laser diode along with a carefully designed protection circuit is now ready for weapon system application and can meet system requirements with high confidence.

References

[1] R. J. Fisher "The Electrostatic Discharge Threat Environment Data Base and Recommended Baseline Stockpile-To-Target Sequence Specifications" SAND88-2658, Albuquerque, NM: Sandia National Laboratories, November 1988.

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